Possible hadronic molecule structure of the Y(3940) and Y(4140)

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Abstract. In the present article we report on evidence for hadronic molecule structures in the charmonium sector. In particular we discuss the $Y(3940)$ and the recently observed $Y(4140)$ as heavy hadron molecule states with quantum numbers $J^{\rm PC} = 0^{++}$ or 2^{++}. The $Y(3940)$ state is considered to be a superposition of $D^{*+}D^{*-}$ and $D^{*0}\overline{D^{*0}}$, while the $Y(4140)$ is a bound state of D_s^{*+} and D_s^{*-} mesons. We give predictions for both the strong $Y(3940) \to J/\psi\omega$, $Y(4140) \to J/\psi\phi$ and radiative $Y(3940)/Y(4140) \to \gamma\gamma$ decay widths in a phenomenological Lagrangian approach. The results for the strong hidden charm decay modes clearly support the molecular interpretation of the $Y(3940)$ and $Y(4140)$, while our estimates for the radiative decays provide a sensitive test for the underlying meson structure of the two Y mesons discussed here. The alternative assignment of $J^{\rm PC} = 2^{++}$ is also tested, giving similar results for the strong decay widths.

Keywords: charm mesons, hadronic molecule, strong and radiative decay
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INTRODUCTION

With the discovery of the charmonium-like X, Y and Z mesons the prospects were raised of possibly identifying a non-trivial structure of a meson resonance. The latest announcement [1] of the narrow state $Y(4140)$ by the CDF Collaboration at Fermilab is just the continuation of a series of previously discovered charmonium-like resonances which are not easily interpreted as conventional quark-antiquark structures. Now the CDF Collaboration has evidence of a narrow near-threshold structure, termed the $Y(4140)$ meson, in the $J/\psi\phi$ mass spectrum in exclusive $B^+ \to J/\psi\phi K^+$ decays with the mass $m_{Y(4140)} = 4143.0 \pm 2.9(\text{stat}) \pm 1.2(\text{syst})$ MeV and natural width $\Gamma_{Y(4140)} = 11.7^{+8.3}_{-5.0}(\text{stat}) \pm 3.7(\text{syst})$ MeV [1]. As already stressed in [1], the new structure $Y(4140)$, which decays to $J/\psi\phi$ just above the $J/\psi\phi$ threshold, shows a similar decay and production pattern to the previously discovered $Y(3940)$ [2, 3], which is also produced in B-decays and was found in the $J/\psi\omega$ decay channel near this respective threshold. The mass and width of the $Y(3940)$ resonance are: $m_{Y(3940)} = 3943 \pm 11(\text{stat}) \pm 13(\text{syst})$ MeV, $\Gamma_{Y(3940)} = 87 \pm 22(\text{stat}) \pm 26(\text{syst})$ MeV (Belle Collaboration [2]) and $m_{Y(3940)} = 3914.6^{+3.8}_{-3.4}(\text{stat}) \pm 2.0(\text{syst})$ MeV, $\Gamma_{Y(3940)} = 34^{+12}_{-8}(\text{stat}) \pm 5(\text{syst})$ MeV (*BABAR* [3]).

The problematic nature of these resonances with respect to their arrangement in the constituent quark model originates in the decay patterns. A conventional pure charmonium state decays dominantly to open charm modes while hidden charm decays would be strongly suppressed [4, 5] due the Okubo, Zweig and Iizuka (OZI) rule. Under the assumption that the $Y(4140)$ is a pure $c\bar{c}$ state a quantitative [6] estimate for the hidden charm $Y(4140) \to J/\psi\phi$ decay width results in the order of a few keV. This is in fact around several orders of magnitude smaller than current data seem to imply for the $Y(4140) \to J/\psi\phi$ decay width. Similarly, the $Y(3940) \to J/\psi\omega$ decay width is larger than 1 MeV [5], orders of magnitude away from the $c\bar{c}$ expectation. This could be signals for nonconventional structures of the $Y(3940)$ and the $Y(4140)$. Possible alternative interpretations involve structures such as hadronic molecules, tetraquark states or even hybrid configurations (for recent reviews see e.g. Refs. [4, 5]).

The closeness of the $D^*\bar{D}^*$ and $D_s^{*+}D_s^{*-}$ thresholds implies a meson-meson bound state structure. But also quantitative analyses based on the possible dynamical generation of both resonances seem to support this interpretation. As a first follow-up to the CDF result it is suggested in [7] that both the $Y(3940)$ and $Y(4140)$ are hadronic molecules in this case in the context of a meson-exchange dynamics. These hadron bound states can have quantum numbers $J^{\rm PC} = 0^{++}$

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or 2^{++} whose constituents are the vector charm $D^*(D_s^*)$ mesons:

$$\begin{aligned} |Y(3940)\rangle &= \frac{1}{\sqrt{2}}\big(|D^{*+}D^{*-}\rangle + |D^{*0}\overline{D^{*0}}\rangle\big)\,, \\ |Y(4140)\rangle &= |D_s^{*+}D_s^{*-}\rangle\,. \end{aligned} \tag{1}$$

Earlier results based on the pion-exchange mechanism already indicated that the $D^*\overline{D^*}$ system can form a bound state [8]. The dominant $D^*\bar{D}^*$ component in the $Y(3940)$ is also confirmed in the coupled channel analysis of [9]. Binding in the $D_s^*\overline{D_s^*}$ channel can be induced by η and ϕ meson exchange [7]. Further on recent QCD sum rule studies [10, 11] also favor a molecular structure of the $Y(4140)$.

In the present article we report on a first quantitative prediction for the decay rates of the observed modes $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ assuming the hadronic molecule structures of Eq. (1) with quantum numbers $J^{\rm PC} = 0^{++}$ (for further details see [12]). Results will be shown to be fully consistent with present experimental observations, strengthening the unusual hadronic molecule interpretation. Further predictions are given for the radiative two-photon decays of these states. Finally, we also consider the alternative $J^{\rm PC} = 2^{++}$ assignment for the Y states.

THEORETICAL BACKGROUND

In order to study the decay properties of hadronic bound objects we use a method based on effective Lagrangians describing the interaction of the particles involved. Other hadron molecules such as the $a_0(980)$, $f_0(980)$, $D_{s0}^*(2317)$, $D_{s1}(2460)$, and $X(3872)$ have already been successfully described and studied with this method (see e.g. [13, 14]). The composite (molecular) structure of the $Y(3940)$ and $Y(4140)$ states is defined by the compositeness condition $Z = 0$ [15, 16] which implies that the renormalization constant of the hadron wave function is set equal to zero. Therefore the hadron exists solely as a bound state of its constituents. As a consequence decay processes of hadron molecules proceed in leading order via meson loops of its constituents.

For the observed $Y(3940)$ and $Y(4140)$ states we adopt the convention that the spin and parity quantum numbers of both states are $J^{\rm PC} = 0^{++}$. Presently the $J^{\rm P}$ quantum numbers are not unambiguously determined yet in experiment except for $C = +$. For example, the $Y(3940)$ is also discussed as a $J^{\rm PC} = 1^{++}$ charmonium candidate [5], but 0^{++} is not ruled out. Their masses are expressed in terms of the binding energy ε_Y as $m_{Y(3940)} = 2m_{D^*} - \varepsilon_{Y(3940)}$ and $m_{Y(4140)} = 2m_{D_s^*} - \varepsilon_{Y(4140)}$, where $m_{D^*} \equiv m_{D^{*+}} = 2010.27$ MeV and $m_{D_s^*} = m_{D_s^{*+}} = 2112.3$ MeV are the masses of the constituent mesons. Since the observed masses are relatively far from the corresponding thresholds we do not include isospin-breaking effects that is we suppose that charged and neutral nonstrange D^* mesons have the same masses. Following Ref. [7] we consider the $Y(3940)$ meson as a superposition of the molecular $D^{*+}D^{*-}$ and $D^{*0}D^{*0}$ configurations, while the $Y(4140)$ is a bound state of D_s^{*+} and D_s^{*-} mesons (see Eq. (1)). For the sake of simplicity we introduce the short notations $Y(3940) \equiv Y_1$ and $Y(4140) \equiv Y_2$. The coupling of the scalar molecular states Y_i to their constituents is expressed by the phenomenological Lagrangians

$$\begin{aligned} \mathscr{L}_{Y_1} &= \frac{g_{Y_1}}{\sqrt{2}} Y_1(x) \int d^4y\, \Phi(y^2) \left\{ D^{*0\mu}\big(x+\frac{y}{2}\big)\,\overline{D^{*0}}_\mu\big(x-\frac{y}{2}\big) + D^{*+\mu}\big(x+\frac{y}{2}\big)\,D^{*-}_\mu\big(x-\frac{y}{2}\big) \right\}, \\ \mathscr{L}_{Y_2} &= g_{Y_2}\, Y_2(x) \int d^4y\, \Phi(y^2)\, D^{*+\mu}\big(x+\frac{y}{2}\big)\, D^{*-}_\mu\big(x-\frac{y}{2}\big)\,, \end{aligned} \tag{2}$$

where g_Y is the respective coupling constant.The interaction Lagrangian is expressed by the center of mass and relative coordinates x and y. The distribution of the constituents inside the molecular states Y_i is expressed by the correlation function $\Phi(y^2)$. The Fourier transform of the correlation function appears as a form factor in our calculations. In the present analysis we have chosen the Gaussian form of $\tilde{\Phi}(p_E^2/\Lambda_Y^2) \doteq \exp(-p_E^2/\Lambda_Y^2)$, where p_E is the Euclidean Jacobi momentum and Λ_Y is a size parameter with a value of about 2 GeV – a typical scale for the masses of the constituents of the Y_i states.

The coupling constants g_Y are determined by the compositeness condition with $Z_{Y_i} = 1 - \Sigma'_{Y_i}(m_Y^2) = 0$, where $\Sigma'_{Y_i}(m_{Y_i}^2) = d\Sigma_{Y_i}(p^2)/dp^2|_{p^2=m_{Y_i}^2}$ is the derivative of the mass operator Σ_{Y_i} generated by $\mathscr{L}_{Y_i}(x)$.

To determine the strong $Y \to J/\psi V$ and two-photon $Y \to \gamma\gamma$ decays we have to include the couplings of $D^*(D_s^*)$ mesons to vector mesons (J/ψ, ω, ϕ) and to photons. The couplings of J/ψ, ω, ϕ to vector $D^*(D_s^*)$ mesons are taken

from the HHChPT Lagrangian [17, 18]:

$$
\begin{aligned}
\mathscr{L}_{D^*D^*J_\psi} &= ig_{D^*D^*J_\psi} J_\psi^\mu \left(D_{\mu i}^{*\dagger} \overleftrightarrow{\partial}_\nu D_i^{*\nu} + D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}^\nu D_{\mu i}^* - D_i^{*\dagger\nu} \overleftrightarrow{\partial}_\mu D_{\nu i}^* \right), \\
\mathscr{L}_{D^*D^*V} &= ig_{D^*D^*V} V_{ij}^\mu D_{\nu i}^{*\dagger} \overleftrightarrow{\partial}_\mu D_j^{*\nu} + 4if_{D^*D^*V} (\partial^\mu V_{ij}^\nu - \partial^\nu V_{ij}^\mu) D_{\mu i}^* D_j^{*\dagger\nu}
\end{aligned} \tag{3}
$$

where $A\overleftrightarrow{\partial}B \equiv A\partial B - B\partial A$, i, j are flavor indices of the diagonal matrix $V_{ij} = \mathrm{diag}\{\omega/\sqrt{2}, \omega/\sqrt{2}, \phi\}$ containing ω and ϕ mesons and $D_i^* = (D^{*0}, D^{*+}, D_s^{*+})$ is the triplet of vector D^* mesons containing light antiquarks $\bar{u}$, $\bar{d}$ and $\bar{s}$, respectively. The chiral couplings $g_{D^*D^*J_\psi}$, $g_{D^*D^*V}$ and $f_{D^*D^*V}$ are taken from [17, 18] The leading-order process relevant for the strong decays $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ is the diagram of Figure 1 involving the vector mesons D^* or D_s^* in the loop. Diagrammatically it already becomes obvious that the meson loop technique provides an opportunity to circumvent the OZI-suppression at lowest order in contrast to corresponding diagrams in the charmonium picture.

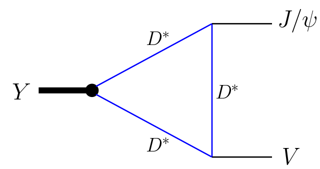

FIGURE 1. Diagram describing the $Y \to J/\psi V$ ($V = \omega, \phi$) decays.

The coupling of the charged $D^{*\pm}(D_s^{*\pm})$ mesons to photons is generated by minimal substitution in the free Lagrangian of these mesons. The corresponding electromagnetic Lagrangian is given by

$$
\begin{aligned}
\mathscr{L}_{\rm em} &= eA_\alpha \left(g^{\alpha\nu} D_\mu^{*-} i\partial^\mu D_\nu^{*+} - g^{\mu\nu} D_\mu^{*-} i\partial^\alpha D_\nu^{*+} + \mathrm{H.c} \right) \\
&+ e^2 D_\mu^{*-} D_\nu^{*+} \left(A^\mu A^\nu - g^{\mu\nu} A^\alpha A_\alpha \right).
\end{aligned} \tag{4}
$$

which diagrammatically leads to the two relevant graphs displayed in Figures 2(a) and 2(b). Since the strong interaction Lagrangian of Eq. 2 is nonlocal it has to be modified in the following way in order to restore full gauge invariance. According to [19] each charged constituent meson field $H^\pm$ in $\mathscr{L}_Y$ is multiplied by the gauge field exponential $H^\pm(y) \to e^{\mp ieI(y,x,P)} H^\pm(y)$, where $I(x,y,P) = \int_y^x dz_\mu A^\mu(z)$. This gives rise to the diagrams in Figures 2(c) and 2(d) which therefore are a consequence of the nonlocality of the present method. The contribution of these additional processes is of the order of a few percent when compared to the leading diagram of Figure 2(a). However, their inclusion is necessary to guarantee full gauge invariance.

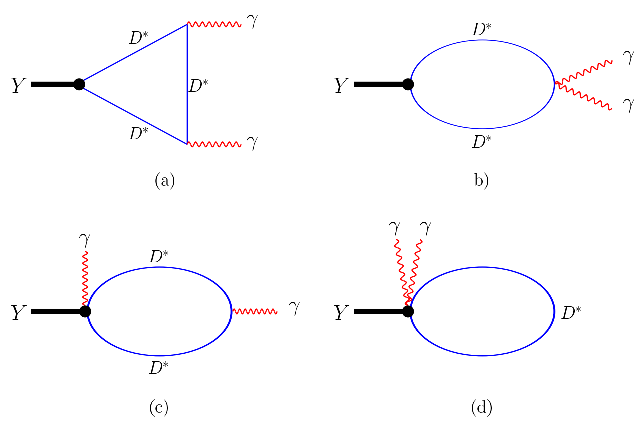

FIGURE 2. Diagrams contributing to the $Y \to \gamma\gamma$ decay.

RESULTS

In the present analysis we studied the strong $J/\psi V$ ($V=\omega,\phi$) and radiative two-gamma decay properties of the $Y(3940)$ and $Y(4140)$ mesons in the framework of the effective Lagrangian approach. Our results for the decay widths are contained in Table 1. The errors of the results reflect the uncertainty of the experimental mass values of the Y states. For the masses of the Y mesons we use the values extracted by the *BABAR* [3] and the CDF [1] Collaborations.

TABLE 1. Decay properties of $Y(3940)$ and $Y(4140)$ for $J^{PC}=0^{++}$.

Quantity	$\mathbf{Y(3940)}$	$\mathbf{Y(4140)}$
$\Gamma(Y\to J/\psi V)$, MeV	5.47 ± 0.34	3.26 ± 0.21
$\Gamma(Y\to\gamma\gamma)$, keV	0.33 ± 0.01	0.63 ± 0.01

The predictions for the couplings g_Y of the Y states to their meson constituents are consistent with a trivial estimate using the Weinberg formula originally derived for the deuteron as based on the compositeness condition [15] with $g_Y^W=\sqrt{32\pi}\,m_{D^*}^{3/4}\,\varepsilon_Y^{1/4}$. This formula represents the leading term of an expansion in powers of the binding energy ε. Note that this expression can be obtained in the local limit (i.e. the vertex function approaches the limit $\Phi(y^2)\to\delta^4(y)$) and when the longitudinal part $k^\mu k^\nu/m_{D^*}^2$ of the constituent vector meson propagator is neglected. The numerical results for the couplings $g^W_{Y(3940)}=9.16$ GeV and $g^W_{Y(4140)}=8.91$ GeV are rather comparable with the nonlocal results $g_{Y(3940)}=14.08$ GeV and $g_{Y(4140)}=13.20$ GeV.

The predictions of $\Gamma(Y(3940)\to J/\psi\omega)=5.47$ MeV and $\Gamma(Y(4140)\to J/\psi\phi)=3.26$ MeV for the observed decay modes are sizable and fully consistent with the upper limits set by present data on the total widths. The result for $\Gamma(Y(3940)\to J/\psi\omega)$ is also consistent with the lower limit of about 1 MeV [5]. Values of a few MeV for these decay widths naturally arise in the hadronic molecule interpretation of the $Y(3940)$ and $Y(4140)$, whereas in a conventional charmonium interpretation the $J/\psi V$ decays are strongly suppressed by the OZI rule [5]. In addition to the possibility of binding the $D^*\bar{D}^*$ and $D_s^{*+}D_s^{*-}$ systems [7], present results on the $J/\psi V$ decays give further strong support to the interpretation of the Y states as heavy hadron molecules.

Further tests of the presented scenario concern the two-photon decay widths, which we predict to be of the order of 1 keV.

TABLE 2. Decay properties of $Y(3940)$ and $Y(4140)$ for $J^{PC}=2^{++}$.

Quantity	$\mathbf{Y(3940)}$	$\mathbf{Y(4140)}$
$\Gamma(Y\to J/\psi V)$, MeV	7.48 ± 0.27	4.41 ± 0.16
$\Gamma(Y\to\gamma\gamma)$, keV	0.27 ± 0.01	0.50 ± 0.01

Finally we also test the $J^{\rm PC}=2^{++}$ assignment for the Y states which is not yet ruled out experimentally. The coupling of the molecular tensor field $Y_{\mu\nu}$ to the meson constituents is set up as

$$\begin{aligned}\mathscr{L}_{Y_1} &= \frac{g_{Y_1}}{\sqrt{2}}\,Y_1^{\mu\nu}(x)\int d^4y\,\Phi(y^2)\,\{D^{*0}_\mu\big(x+\frac{y}{2}\big)\,\overline{D^{*0}}_\nu\big(x-\frac{y}{2}\big)+D^{*+}_\mu\big(x+\frac{y}{2}\big)\,D^{*-}_\nu\big(x-\frac{y}{2}\big)\}\\ \mathscr{L}_{Y_2} &= g_{Y_2}\,Y_2^{\mu\nu}(x)\int d^4y\,\Phi(y^2)\,D^{*+}_\mu\big(x+\frac{y}{2}\big)\,D^{*-}_\nu\big(x-\frac{y}{2}\big)\end{aligned}\qquad(5)$$

Proceeding as outlined before we obtain the results in Table 2. Since the results for the strong J/ψ decays are quite similar to the 0^{++} case, a 2^{++} scenario cannot be ruled out and is also consistent within a molecular interpretation of the Y states.

Quite recently the BELLE Collaboration [20] searched for the $Y(4140)$ in the two-photon process $\gamma\gamma\to J/\psi\phi$, however without evidence so far. In this framework they tested our prediction for the $Y(4140)\to\gamma\gamma$ decay width by experiment and obtained $\Gamma_{\gamma\gamma}(Y(4140))\mathscr{B}(Y(4140)\to J/\psi\phi)<40$ eV [20] for $J^P=0^+$ which results in a much smaller upper bound for the two-photon widths of about 0.2 keV. This finding is presently in conflict with a possible molecular interpretation of the $Y(4140)$.

The search for charmonium-like states in the process $\gamma\gamma\to J/\psi\omega$ by the BELLE Collaboration [21] resulted in an enhancement with mass $M=3915\pm3\pm2$ MeV denoted by $X(3915)$. According to its mass and width it is a possible

candidate for the $Y(3940)$. The observed 2γ decay properties also support the $D^*\bar{D}^*$ bound state interpretation since the measured quantity, the product of the 2γ width and the branching ratio, $\Gamma_{\gamma\gamma}(X(3915))\mathscr{B}(X(3915) \to \omega J/\psi) = 61 \pm 17 \pm 8$ eV ($J^P = 0^+$) is of the same order of magnitude as the present results in Table 1.

CONCLUSIONS

The properties of the hidden-charm and two-photon decay modes of the charmonium-like mesons $Y(3940)$ and $Y(4140)$ are discussed under the assumption that both are bound states of charm mesons. The method used in the present analysis constitutes a consistent field theoretical tool for hadronic bound states and fulfills full gauge invariance. In case of the hidden charm decays $Y(3940) \to J/\psi\omega$ and $Y(4140) \to J/\psi\phi$ the sizable results for the widths obtained in the effective Lagrangian approach are in good agreement with available data and clearly support the hadron molecule assignment. A $c\bar{c}$ scenario is disfavored since, in contrast to the hadron molecule, the estimated widths is negligible in this case.

In addition the two-photon decays can provide a sensitive test for the meson structure as well. In case of the 2γ width of the $Y(4140)$ available data predict a much smaller width. Note that if the present experimental upper limit for the 2γ decay width is even lower it will be very hard to explain this state as a hadronic molecule. In contrast the $Y(3940) \to \gamma\gamma$ decay width together with the sizable $J/\psi\omega$ branching ratio obtained within the $D^*\bar{D}^*$ bound state interpretation are comparable to experimental observations.

However, more and particularly precise experimental information on these Y states is necessary. A full interpretation of the $Y(3940)$ and $Y(4140)$ states requires an experimental determination of the J^{PC} quantum numbers, a consistent and hopefully converging study of binding mechanisms in the $D^*_{(s)}\overline{D^*_{(s)}}$ systems and finally a full understanding of the open charm decay modes, such as $D\bar{D}$, $D\bar{D}^*$, $D\bar{D}^*\gamma$, etc., which are also naturally fed in a charmonium picture.

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